## Magnetic Fields of Neutron Stars: an Overview

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**Abstract.** Observations indicate that magnetic fields on neutron stars span at least the range  $10^{8-15}$  G, corresponding to a range of magnetic fluxes similar to that found in white dwarfs and main sequence stars. The observational evidence is discussed, as well as the possible origin of the field, and the associated phenomenology ("classical", millisecond, and binary pulsars, "magnetars", etc.). Particular attention is given to physical processes potentially leading to magnetic field evolution.

### 1. Introduction

Neutron stars are dense, compact remnants of evolved stars, with degenerate fermions compressed by strong gravitational fields (e.g., Shapiro & Teukolsky 1983). Their structure is set almost entirely by one parameter, their mass. The latter can be measured with some accuracy only in binary systems containing a pulsar, where its distribution is found to be consistent with a narrow Gaussian, centered at  $1.35M_{\odot}$  and with width  $0.04M_{\odot}$  (Thorsett & Chakrabarty 1999), so one might presume that neutron stars are essentially all identical. This is far from true. A wide range of rotation rates and magnetic fields, together with the presence or absence of mass-transfering binary companions, allow for a rich phenomenology. Among single (or non-accreting binary) neutron stars, we distinguish "classical" pulsars, millisecond pulsars, soft gamma-ray repeaters, anomalous x-ray pulsars, and inactive, thermal x-ray emitters. Binary systems with mass transfer onto a neutron star can be divided into high-mass and lowmass x-ray binaries (according to the companion mass), with substantially different properties. Magnetic fields play an essential role by accelerating particles, by channeling these particles or accretion flows, by producing synchrotron emission or resonant cyclotron scattering, and by providing the main mechanism for angular momentum loss from non-accreting stars. It is even speculated that in some objects the magnetic field may be the main energy source for the observed radiation.

I begin by reviewing several observational "classes" of neutron stars mentioned above, with a special eye on the evidence for the presence and strength of the magnetic fields in each class (§2). In §3, the resulting magnetic fluxes are compared to those of other kinds of stars, and possible connections are discussed. Section 4 surveys the evidence for and against magnetic field evolution, and discusses physical processes which may lead to such evolution. General conclusions are presented in §5.

## 2. Classes of neutron stars and evidence for magnetic fields

# 2.1. Radio pulsars

Radio pulsars are regularly pulsating sources of radio waves, interpreted as magnetized, rotating neutron stars (Pacini 1967; Gold 1968). Beams of radiation emerging from the poles of a roughly dipolar magnetic field misaligned with respect to the rotation axis appear as pulses every time they sweep the location of the Earth. These pulses reveal rotation periods (P) from 1.55 milliseconds (ms) to several seconds, which lengthen with time  $(\dot{P} > 0)$ .

The simplest model for the spin-down process is to consider the neutron star as a magnetized body of moment of inertia I, rotating in vacuum with angular velocity  $\vec{\Omega}$  (Ostriker & Gunn 1969). It loses rotational energy due to the time-variation of its magnetic dipole vector  $\vec{\mu}$ , which is rotating at a fixed inclination  $\alpha$  with respect to to the rotation axis,

$$-\frac{d}{dt}\left(\frac{1}{2}I\Omega^{2}\right) = \frac{2}{3c^{3}}|\ddot{\vec{\mu}}|^{2} = \frac{1}{6c^{3}}B^{2}R^{6}\Omega^{4}\sin^{2}\alpha,\tag{1}$$

which allows us to infer the dipole magnetic field strength,  $B[G] \approx 3.2 \times 10^{19} \sqrt{P[s]\dot{P}}$  (for radius R=10 km,  $I=10^{45} \mathrm{g \ cm^2}$ , and  $\alpha=90^\circ$ ).

This "dipole in vacuum" model is unlikely to be very accurate, as real pulsars are surrounded by a magnetosphere, and by an interstellar medium whose plasma frequency is much higher than the expected radiation, which therefore can't propagate. Somewhat more realistic models (e.g., Goldreich & Julian 1969) tend to roughly confirm the estimate of B (being less sensitive to  $\alpha$ ), so this estimate is generally used. Assuming a constant field strength and moment of inertia, eq. (1) can be integrated backwards in time to give a divergent rotation rate at a time  $\tau = \Omega/(-2\dot{\Omega}) = P/(2\dot{P})$  before the present (at which the spin parameters are to be evaluated), defining a characteristic "spin-down age" for the pulsar.

In terms of these parameters, radio pulsars fall into two fairly disjoint groups (e.g., Phinney & Kulkarni 1994):

- young ( $\tau \sim 10^{3-7}$  yr), relatively slow ( $P \sim 16$  ms to several seconds), and strongly magnetized ( $B \sim 10^{11-13}$  G) "classical" pulsars, and
- old  $(10^{8-10} \text{ yr})$ , fast (1.55 to several ms), and weakly magnetized  $(10^{8-9} \text{ G})$  "millisecond" pulsars.

Confirming that  $\tau$  is related to true age, many of the "youngest" classical pulsars are found to be associated with supernova remnants (which disperse after  $\sim 10^5$  yr), and many millisecond pulsars (but no classical pulsars) are found in globular clusters. An additional difference between the two classes is that most millisecond pulsars are found in binary systems (in most cases with old white dwarf companions), whereas the vast majority of classical pulsars are single.

One problem with this general picture is that, in the few cases where it is possible to measure  $\ddot{\Omega}$  (all of which are young pulsars), the so-called braking index  $n \equiv \Omega \ddot{\Omega} / \dot{\Omega}^2$  does not agree with the canonical n=3 predicted in

the dipole spin-down model, but has significantly *smaller* values, which differ from one pulsar to another (e.g., Kaspi et al. 1994). The inclusion of higher multipoles (e.g., quadrupole electromagnetic or gravitational radiation) worsens the problem. This means that the *inferred* magnetic dipole moment in young pulsars *increases* with time. Whether this corresponds to a true increase of the star's dipole moment has not been settled (Blandford 1994).

## 2.2. Magnetars

Two puzzling kinds of astronomical objects have in recent years found a likely interpretation as very highly magnetized neutron stars (see Thompson 2000 for a review):

- Soft gamma-ray repeaters (SGRs) are a class of (so far) 4 objects which repeatedly emit bursts of gamma-rays, in addition to persistent x-rays. For two of these sources, regular pulses have been observed in the persistent x-ray emission, allowing the measurement of a rotation period and period derivative (Kouveliotou et al. 1998; Hurley et al. 1999).
- Anomalous x-ray pulsars (AXPs) show persistent x-ray emission, modulated at a stable, slowly lengthening period. Contrary to the standard, binary x-ray pulsars (§2.3), they show no evidence for a companion star (see Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995; Mereghetti 2000).

Aside from the presence of bursts in the SGRs, these two classes of objects appear to be very similar. All measured periods lie in the narrow range 5-12 s, and objects in both classes are associated with supernova remnants (e.g., Kaspi 2000), arguing for an interpretation as young neutron stars, in rough agreement with characteristic ages inferred from spin-down. In both classes of objects, the persistent x-ray luminosity is much larger than the inferred spin-down power. Therefore, unlike the case of radio pulsars, rotation can not be a significant energy source. The dipole fields inferred from the spin-down rate are  $10^{14-15}$ G, much larger than in previously known classical radio pulsars, though pulsars with similar inferred dipole fields have recently been found (Camilo et al. 2000). It has long been suggested that magnetic energy may be the ultimate source of both the bursts and the persistent radiation (Duncan & Thompson 1992; Paczynski 1992; Thompson & Duncan 1995, 1996), but this would still require a total magnetic energy significantly larger than inferred from the dipole field, i.e. a buried and/or disordered magnetic flux. In any case, the strong magnetic field may modify the radiation transport in the surface layers, so that these objects radiate a much larger fraction of their fossil heat in x-rays (as opposed to neutrinos) than less magnetic neutron stars (Hevl & Hernquist 1997a, b).

## 2.3. X-ray binaries

Neutron stars accreting from binary companions are a vast field of research on their own, which I cannot possibly cover here. I only point out that neutron stars with high-mass companions tend to appear as x-ray pulsars, in which the accreted material is channeled by the magnetic field onto the polar caps, whereas low-mass companions tend to live with non-pulsating neutron stars, in

which the field is presumably not strong enough to channel the accretion flow. In some members of the first class, cyclotron features have been found in the x-ray spectrum, corresponding to  $B \sim (1-4) \times 10^{12}$  G (e.g., Makishima et al. 1999). Note that these are the only direct measurements of neutron star magnetic fields, akin to the many measurements of magnetic fields on white dwarfs and other stars. Assuming that these objects differ from (similarly young) classical radio pulsars only by the presence of the nearby companion, this would give evidence that the field of neutron stars is organized on a relatively large scale, so the surface field and the dipole field are of comparable magnitude.

#### 3. Kinship

Most, if not all, neutron stars descend from main sequence stars with masses  $M_{MS} \gtrsim 8 M_{\odot}$ , i.e., O and early B stars, while lower mass main sequence stars give rise to white dwarfs. We have learned that a fraction of early-type stars (Ap/Bp stars) have strong, highly organized magnetic fields (see the presentations of G. Mathys, J.D. Landstreet, S. Bagnulo, and N. Piskunov in this volume). The same is true for a fraction of the white dwarfs, which tend to be more massive than their non-magnetic counterparts (G. Schmidt, this volume), and therefore plausibly more closely related to neutron stars.

It has long been known that the magnetic fluxes of magnetic white dwarfs and neutron stars are similar (e.g., Ruderman 1972), suggesting a common origin, possibly through flux conservation during the evolution from some progenitor phase. Although much more strongly magnetic objects have been discovered in recent years, the most strongly magnetic main sequence stars (Ap/Bp stars with  $R \sim \text{few } R_{\odot}$  and  $B \sim 3 \times 10^4$  G; e.g. Landstreet 1992), white dwarfs  $(R \sim 10^{-2} R_{\odot}, B \sim 10^9$  G; e.g., Wickramasinghe & Ferrario 2000), and neutron stars (magnetars with  $R \sim 10^{-5} R_{\odot}$  and  $B \sim 10^{15}$  G; see §2.2) still turn out to have remarkably similar magnetic fluxes,  $\Phi = \pi R^2 B \sim 10^{5.5} R_{\odot}^2$  G, despite vast differences in size, density, and magnetic field strength. Lower limits on magnetic fluxes can unfortunately not be compared, as the magnetic fields of most non-degenerate stars and white dwarfs are too weak to be detected. Of course, we may also not yet know the most magnetic stars, if they are scarce or manifest themselves phenomenologically in a way we have not yet identified.

Another interesting point is as follows. Early-type stars have convective cores and radiative envelopes. The mass of the convective core,  $M_{conv}$ , is a strongly increasing function of the total mass of the star,  $M_{MS}$  (e.g., Kippenhahn & Weigert 1994). The mass of the eventual compact remnant,  $M_{rem}$ , is a much more weakly increasing function of  $M_{MS}$  (e.g., Weidemann 1987). The two curves cross at  $M_{MS} \approx 3-4M_{\odot}$  ( $\sim$  A0 stars), where  $M_{conv}=M_{rem}\approx 0.7M_{\odot}$ , a plausible dividing line between magnetic (massive) and non-magnetic (low-mass) white dwarfs (cf. G. Schmidt, this volume). A possible interpretation is that during the main sequence phase the field exists only in the convective core of most early-type stars. (A coherent, equipartition-strength field filling the convective core of a  $4M_{\odot}$  main sequence star produces approximately the maximum flux estimated above.) If it remains confined to the same region during the later stages of evolution, then low-mass white dwarfs have a magnetized region buried in their interior and covered by an unmagnetized envelope (formerly part of the

radiative envelope on the main sequence), whereas massive white dwarfs and neutron stars form exclusively from magnetized material, and therefore have a strong surface field.

#### 4. Magnetic field evolution

#### 4.1. Observational evidence

Several arguments point toward the possibility of an evolving magnetic field in neutron stars:

- 1) Generally speaking, young neutron stars appear to have strong magnetic fields  $\sim 10^{11-15}$  G ("classical" radio pulsars, "magnetars", x-ray pulsars), whereas old neutron stars have weak fields  $\lesssim 10^9$  G (ms pulsars, low-mass x-ray binaries). If these two groups have an evolutionary connection, their dipole moment must decay. Millisecond pulsars are believed to have been spun up to their fast rotation by accretion from a binary companion, a remnant of which is in most cases still present (e.g., Phinney & Kulkarni 1994). Accretion may be the direct or indirect cause of the reduction in the magnetic dipole moment, or it may just be an effect of age.
- 2) Studies of the pulsar distribution on the  $P \dot{P}$  diagram (analogous to "normal" stellar population synthesis studies on the HR diagram) have led to the claim that the magnetic torque decays on a time scale comparable to the life span of "classical" pulsars (Gunn & Ostriker 1970). The case for this claim was strengthened by the simultaneous consideration of pulsar space velocities and their spatial distribution perpendicular to the plane of the Galaxy (e.g., Narayan & Ostriker 1990), but was later put in doubt by other authors (e.g., Bhattacharya et al. 1992), whose more careful analysis leads to opposite results.
- 3) If magnetar emission is powered by magnetic energy (Thompson & Duncan 1996), then the rms magnetic field  $\langle \vec{B}^2 \rangle^{1/2}$  must decay.
- 4) A possible explanation for the "anomalous" braking indices n < 3 in young neutron stars is that their magnetic dipole moment increases with time.

In the remainder of this section, I discuss the physical mechanisms that may lead to such an evolution of the magnetic field.

### 4.2. Physics of spontaneous field evolution

The composition of neutron star matter is still highly uncertain (e.g., Lattimer & Prakash 2000), but it seems almost inevitable that it will contain both neutral particles (plausibly neutrons) and charged particles (protons, electrons, and possibly others). All particles are highly degenerate. The relativistic energies of the electrons reduce their cross-section for colliding against protons, and most of the phase space for final states is blocked by the Pauli principle, leading to a high conductivity and consequently to an Ohmic decay time longer than the age of the Universe (Baym, Pethick, & Pines 1969b). Therefore, little diffusion of the magnetic field can occur.

Can the magnetic field move with the fluid matter inside the neutron star, driven by magnetic stresses or buoyancy forces? Not in an obvious way. The matter in an equilibrium neutron star is fully catalyzed, i.e., weak interactions have had time to bring each fluid element into chemical equilibrium, minimiz-

ing its free energy by distributing baryon number optimally among different "flavors" of particles. This optimal distribution is density-dependent, giving rise to a mechanically stable composition gradient (Pethick 1992; Reisenegger & Goldreich 1992), regardless of the uncertainties in the composition (Reisenegger 2001). Even in the simplest and most favorable scenario, in which the matter is mostly neutrons, with a small ( $\sim 1\%$ ) "impurity" of protons and electrons, magnetic stresses of order the "impurity" contribution to the fluid stresses are required to overcome the stabilizing forces, demanding a magnetic field  $\gtrsim 10^{17}$  G. At lower field strengths, the magnetic stresses can only build up a small chemical imbalance, and evolve on a timescale determined by the weak interactions which erase this imbalance.

This leads to ask whether the magnetic field could move only with the charged particles, leaving the neutral particles behind. This question was addressed in a simple model (Goldreich & Reisenegger 1992) in which protons and electrons move under the effect of electromagnetic forces through a static and uniform neutral background, scattering against each other and against this background. It leads to the following evolution law for the magnetic field,

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left( \vec{v} \times \vec{B} \right) + \gamma \nabla \times \left( -\frac{\vec{j}}{n_e e} \times \vec{B} \right) - \nabla \times \left( \frac{c}{\sigma} \vec{j} \right), \tag{2}$$

where  $\vec{v}$  is a weighted average velocity of all charged particles,  $\vec{j} = c\nabla \times \vec{B}/(4\pi)$  is the electric current (due to relative motions of the charged particles),  $n_e$  is the density of protons and electrons, e is the proton charge, c is the speed of light,  $\sigma$  is an isotropic conductivity, limited by inter-particle collisions, and  $\gamma$  is a dimensionless factor ( $|\gamma| < 1$ ) whose magnitude and sign depends on the relative coupling of protons and electrons to the neutral background. Each term on the right-hand side has a familiar (astro-)physical interpretation, in turn:

- 1) Advection of the magnetic flux by a flow of charged particles, i.e., ambipolar diffusion, familiar from star formation (e.g., T. Mouschovias, this volume): The bulk flow arises from magnetic stresses or buoyancy forces acting on the charged particles, and is impeded by inter-particle collisions. It can be decomposed into two modes, one curl-free and one divergence-free, the first of which will be choked by the chemical potential gradients it builds up in the charged particles, and can only be effective if weak interactions can reduce these gradients. Since the driving forces are  $\propto B^2$ , this term is  $\propto B^3$ , becoming much more effective at high field strengths.
- 2) Advection of the magnetic flux by the electric current, or *Hall effect:* This is a "passive" or "kinematic" effect, not "driven" by any forces and which by itself does not change the magnetic energy. However, it is nonlinear ( $\propto B^2$ ) and could possibly lead to small-scale structures in the magnetic field, particularly in the solid crust, where ambipolar diffusion cannot occur.
- 3) The familiar resistive or Ohmic diffusion: Linear in B; it is quite ineffective for a large-scale field, but may play a role in dissipating small-scale structures created by the other (nonlinear) processes.

For the flows disturbing chemical equilibrium (bulk flow and curl-free ambipolar diffusion), the timescale is set by weak interactions, which also produce the early cooling of neutron stars (through neutrino emission), and which are strongly temperature dependent. Therefore, if  $B \lesssim 10^{17}$  G, the only way in

which these processes can be effective before the star cools down is to keep it hot by some other mechanism, such as dissipation of magnetic energy (e.g., Thompson & Duncan 1996). However, even this is not guaranteed to work, since most of the dissipated energy will be emitted in the form of neutrinos. If the field is strong enough to create a substantial chemical imbalance ( $B \geq 10^{16}$  G), the enhanced neutrino emission may even lead to faster cooling.

None of these mechanisms appear to be interesting at field strengths and time scales relevant to classical or millisecond radio pulsars, unless the magnetic field is confined to a thin layer in the outer crust of the star, where the conductivity is reduced and a combination of Hall drift and Ohmic dissipation may become effective. In magnetars, the high field strength makes both the Hall drift and the ambipolar diffusion quite fast, and their interaction may lead to interesting dynamics, particularly if the rms interior field is somewhat higher than the inferred dipole field, as required from energetic arguments.

This discussion did not consider the formation of superfluid and superconducting states, which probably occurs early in the evolution of a neutron star (Baym, Pethick, & Pines 1969a), concentrating vorticity and magnetic flux into quantized ropes. At moderate to low temperatures, the neutron star fluid will be much more complicated than in the description given above (Mendell 1998). The effect of these complications on magnetic field evolution are not yet well-understood, though much has been speculated. I will refrain from further discussion of these issues.

#### 4.3. Induced field evolution

Aside from the mechanisms for spontaneous evolution, external agents may also change the magnetic field of a neutron star:

- 1) The strong thermal gradient in a cooling protoneutron star is able to overcome the stratifying effect of the chemical gradient, leading to convection. At the same time, the star has not had time to transport angular momentum and will be differentially rotating. As discussed several times in this conference, this combination naturally acts as a dynamo, which is an alternative to the "fossil flux" idea to give rise to the magnetic field in neutron stars (Thompson & Duncan 1993).
- 2) The thermal gradient persists for a much longer time in the outer crust of the star, where it may act as a battery, again giving rise to a substantial field (Urpin & Yakovlev 1980; Blandford, Applegate, & Hernquist 1983; Wiebicke & Geppert 1996 and references therein). This may in principle explain an increasing field in a young neutron star, as suggested by the braking index measurements.
- 3) Accretion from a binary companion is a natural (and popular) way of decreasing the magnetic dipole moment, although there is no agreement on the exact physics involved. Perhaps the most interesting candidate process is the burial of the magnetic flux by the accreted, highly conducting plasma (Bisnovatyi-Kogan & Komberg 1975; Romani 1993). No full models of this process have been produced so far, and three-dimensional simulations will eventually be needed to make sure all possible instabilities have been taken into account. If effective, this process still begs the question of why after its completion a minute, but fairly constant fraction of the initial dipole moment is left or regenerated

to be detectable in ms pulsars. (Note that ms pulsars do *not* appear to be the "tip of the iceberg" of a distribution extending down to much lower fields, since the death rate of their progenitor low-mass x-ray binaries already can barely account for the detectable ms pulsars; e.g., Phinney & Kulkarni 1994; White & Ghosh 1998.)

### 5. Conclusions

The subject of magnetic fields in neutron stars has still much to offer and to demand from us. Little is known about the structure of the field, but nevertheless there is a rich phenomenology asking to be interpreted. The origin and evolution of the field is as uncertain as in all other kinds of stars. Interesting physics is at play, and there may be connections between the magnetic fields of neutron stars, their white dwarf cousins, and the main-sequence progenitors of both. It is likely that advances in the understanding of the respective magnetic fields will support each other if sufficient communication is maintained among the communities of experts, as occurred so well in the present meeting.

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#### Discussion

VAN BALLEGOOIJEN: What is the frequency of the radiation responsible for the energy loss from pulsars? What are the physical processes involved?

REISENEGGER: Taking the magnetic dipole spin-down model seriously, we expect the radiation to be nearly monochromatic at twice the rotation frequency of the star. This is far below the plasma frequency of the interstellar medium, so this radiation cannot propagate. In practice, the spin-down appears to occur through more complicated processes which are not really understood, but almost certainly involve the acceleration of charged particles and the resulting synchrotron and "curvature" radiation (the latter being due to relativistic particles moving along curved magnetic field lines). I don't think there is a theoretical prediction for the resulting spectrum. Observationally, the spectral energy distribution  $(\nu F_{\nu})$  from pulsars has a wide peak at high energies (GeV gamma-rays to hard x-rays), where most of the energy is emitted. It falls towards lower energies, from the ultraviolet to the radio. The bolometric radiation output, although uncertain due to incomplete frequency coverage and beaming effects, appears to vary from a small fraction of the pulsar spin-down power in the most energetic pulsars to a substantial fraction in less energetic objects. The remainder of the energy is carried away by a wind and eventually deposited in the surrounding "plerion" nebula.

STRASSMEIER: Does the polarisation of the radio signal (or any other radiation that you may detect) tell something about the magnetic field?

STAIRS: The polarization can tell us about the geometry of the magnetic field in the emitting region, but not about its magnitude. The latter is obtained exclusively from timing of the pulsar spin-down.

HENRICHS: Could you comment on alignment between the magnetic and rotation axis as a possible mechanism to cause the apparent decay of the field?

REISENEGGER: In the standard dipole spin-down model, this is clearly a possibility, as we are only sensitive to the dipole component perpendicular to the rotation axis. This has been explored several times, most recently by Tauris and Manchester. Theoretically, it doesn't appear much easier to align the dipole than to make it disappear, though people are clever and do come up with ideas. In addition, slightly more sophisticated models for the spin-down process, such as the early one by Goldreich and Julian, predict spin-down even when the dipole is aligned with the rotation axis (the only case considered in that particular work), which seems to imply that the spin-down process is not very sensitive to the orientation of the magnetic dipole.

SCHMIDT: What fraction of neutron stars is magnetic? In other words, how does the pulsar birth rate compare to the core-collapse supernova rate?

REISENEGGER: That ratio is hard to nail down, as both the numerator and the denominator have large error bars which are difficult to quantify. From statistics alone, we cannot safely discard, on the one hand, that all supernovae produce pulsars or, on the other, that only a modest fraction do. However, it is interesting to note that many young supernova remnants do not contain detectable radio pulsars but rather x-ray sources (AXPs, SGRs, "quiescent" neutron stars) or no compact source whatsoever.